

# Barriers and enablers for prescribed burns for wildfire management in California

Rebecca K. Miller <sup>1\*</sup>, Christopher B. Field <sup>2,3</sup> and Katharine J. Mach <sup>2,4,5</sup>

**Prescribed burns to reduce fuel can mitigate the risk of catastrophic wildfires. However, multiple barriers limit their deployment, resulting in their underutilization, particularly in forests. We evaluate sociopolitical barriers and opportunities for greater deployment in California, an area recurrently affected by catastrophic fires. We use a mixed-methods approach combining expert interviews, state legislative policy analysis and prescribed-burn data from state records. We identify three categories of barriers. Risk-related barriers (fear of liability and negative public perceptions) prevent landowners from beginning the burn planning process. Both resource-related barriers (limited funding, crew availability and experience) and regulations-related barriers (poor weather conditions for burning and environmental regulations) prevent landowners from conducting burns, creating a gap between planning and implementation. Recent policies have sought to address mainly risk-related challenges, although these and regulations-related challenges remain. Fundamental shifts in prescribed-burn policies, beyond those currently under consideration, are needed to address wildfires in California and worldwide.**

Catastrophic wildfires have increased in the Western United States in recent years, and particularly in California<sup>1</sup>. These fires stem from a combination of climate change that has heightened hot and dry conditions<sup>2</sup>, historic fire suppression policies that have enabled nearly a century of fuel (wood and other plant material) accumulation<sup>2,3</sup> and insufficient fuel treatments that have removed too few of the accumulated fuels from the landscape<sup>4,5</sup>. Fuel treatments are activities intended to reduce the incidence or severity of wildfires. Twenty million acres of forest land, or nearly 20% of California, would benefit from fuel treatments. While the northern forested regions of California have experienced a fire deficit recently, referring to long-term declines in burning, the state's southern chaparral has suffered more fire than its historic fire regime<sup>6</sup>. Addressing the existing fire deficit across the state will require decades of fuel treatments at a far greater pace and scale than those implemented today<sup>5</sup>.

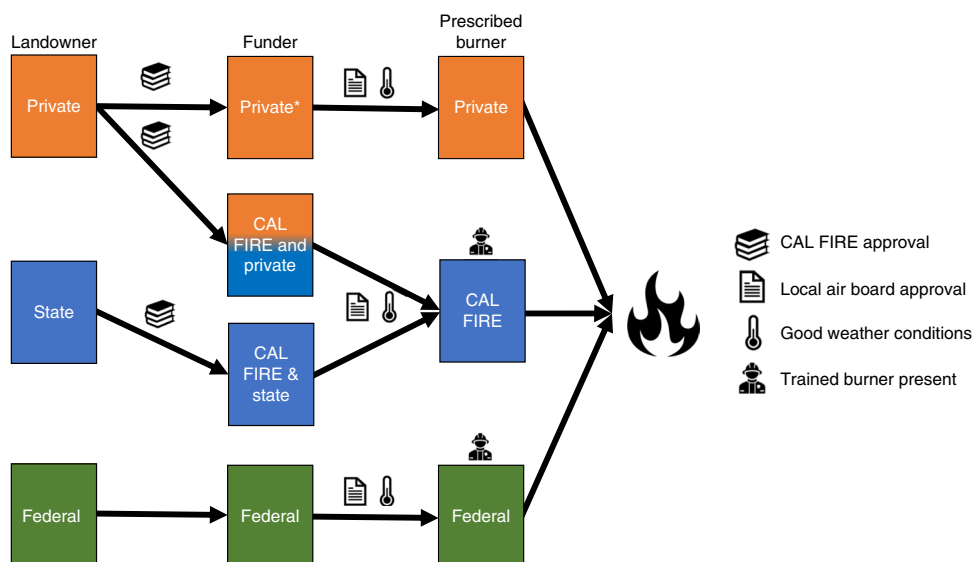
Fuel treatments primarily encompass prescribed burns, mechanical thinning and managed wildfire. Prescribed burns are fires purposefully set under controlled conditions to clear ground fuel. Mechanical thinning uses hand-held or tractor-mounted tools to move ladder fuel to the ground or to sites for burning or removal. Managed wildfire occurs when federal agencies allow natural ignitions to burn in remote areas, essentially a wildfire but relying on remoteness and careful monitoring of weather conditions to minimize danger to the public<sup>6,7</sup>. Prescribed burns return fire to the landscape (an intrinsic part of such ecosystems), provide ecological benefits and, unlike managed wildfire, can occur near developed areas and on private, state or federal lands<sup>6,8</sup>. Prescribed burns remove the ground fuel that enables easier fire spread, unlike most mechanical thinning methods. Prior studies have examined the efficacy of fuel treatments in forests; prescribed burns remove fuels more effectively than mechanical thinning alone, but combining the two methods is best<sup>9–11</sup>. Infrequent fuel treatments have resulted in excessive fuels in forested landscapes, which often need preliminary

mechanical thinning before implementing prescribed burns<sup>3,10,12</sup>. Although less effective than prescribed burns alone, mechanical thinning remains a valuable fuel treatment option throughout forested areas<sup>12,13</sup>. While uncertainties remain regarding the precise effectiveness of treatments, this study is predicated on the recognition that they reduce wildfire risk and are underdeployed throughout California<sup>5,14–16</sup>. Addressing wildfire risks will require initial treatments and subsequent retreatments across millions of acres<sup>6</sup>; see Supplementary Notes for additional information.

This paper focuses on prescribed burns and their potential to address California's fire deficit and recent policy proposals emerging from the 2017 and 2018 wildfires that pertained to the deployment of prescribed burns. The devastating California wildfires of 2017 and 2018 may have opened a critical window for nonlinear policy change for prescribed burns and wildfire prevention. Understanding barriers to more prescribed burns and the opportunities to address these barriers is critical to increasing their deployment. In this study, we evaluate burn practices, policies and perspectives regarding fuel treatments in California. We explore perceptions of a range of key stakeholders (federal and state government employees, state legislative staff, non-profit representatives and academics). For prescribed burns in particular, we also investigate the perceived barriers and enablers to increasing deployment.

For this evaluation, we analyse state legislation, prescribed-burn records and transcripts from 40 interviews with 45 interviewees (Supplementary Table 2; see Methods). Interviewees were key participants in California's prescribed-burn policy conversations and represented diverse backgrounds. Interviewees responded to questions about their attitudes toward fuel treatments and about policy challenges and opportunities for increased deployment of prescribed burns. We analysed interviews using a comprehensive, iterative coding analysis to characterize their perspectives. These perspectives are structured around themes that may not reflect broader empirical knowledge of fuel treatments, but have

<sup>1</sup>Emmett Interdisciplinary Program in Environment and Resources, Stanford University, Stanford, CA, USA. <sup>2</sup>Department of Earth System Science, Stanford University, Stanford, CA, USA. <sup>3</sup>Woods Institute for the Environment, Stanford University, Stanford, CA, USA. <sup>4</sup>Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. <sup>5</sup>Leonard and Jayne Abess Center for Ecosystem Science and Policy, University of Miami, Coral Gables, FL, USA. \*e-mail: [rkmiller@stanford.edu](mailto:rkmiller@stanford.edu)



**Fig. 1 | Process to conduct a prescribed burn by landowner.** Private, state and federal landowners have distinct approaches and requirements for conducting prescribed burns in California. Private landowners can either conduct a burn themselves under good weather conditions and with approval from CAL FIRE and the local air board, or can partner with CAL FIRE. State agencies partner with CAL FIRE and burn under good weather conditions, with trained burners present and with approval from CAL FIRE and the local air board. Federal agencies burn under good weather conditions, with local air board approval and with trained burners present. Asterisk notes that some external grants are available that enable burns at reimbursable or no cost through local governments or non-profit organizations.

important policy and practice implications because, given their positions, interviewees can propose or institute new policies, and so their perspectives may indicate future policy directions.

## Results

**Current state of prescribed burns.** According to interviewees, different landowners have distinct pathways to conducting prescribed burns, resulting in landowner-specific challenges. Interviewees characterized the complexity of the burning process on private, state and federal lands (Fig. 1). Private landowners can either (1) conduct and pay for burns with permits from the California Department of Forestry and Fire Protection (CAL FIRE) and approval from their local air board or (2) contract with CAL FIRE through the Vegetation Management Program (VMP). Through the VMP, state agencies and private landowners partner with CAL FIRE and pay for burns on a sliding-cost scale determined by the financial benefits accrued by the landowner. CAL FIRE conducts the burn, maintains responsibility for any escapes and pays for its share through the California Climate Investments. CAL FIRE can burn only under good weather conditions and with approval from the local air board. The federal government can burn under good weather conditions, with local air board approval, and if prescribed burns are included in site-specific federal plans. Conducting a prescribed burn anywhere in California requires a burn plan, state and local air board approval, good weather conditions and trained personnel (unless conducted by private landowners).

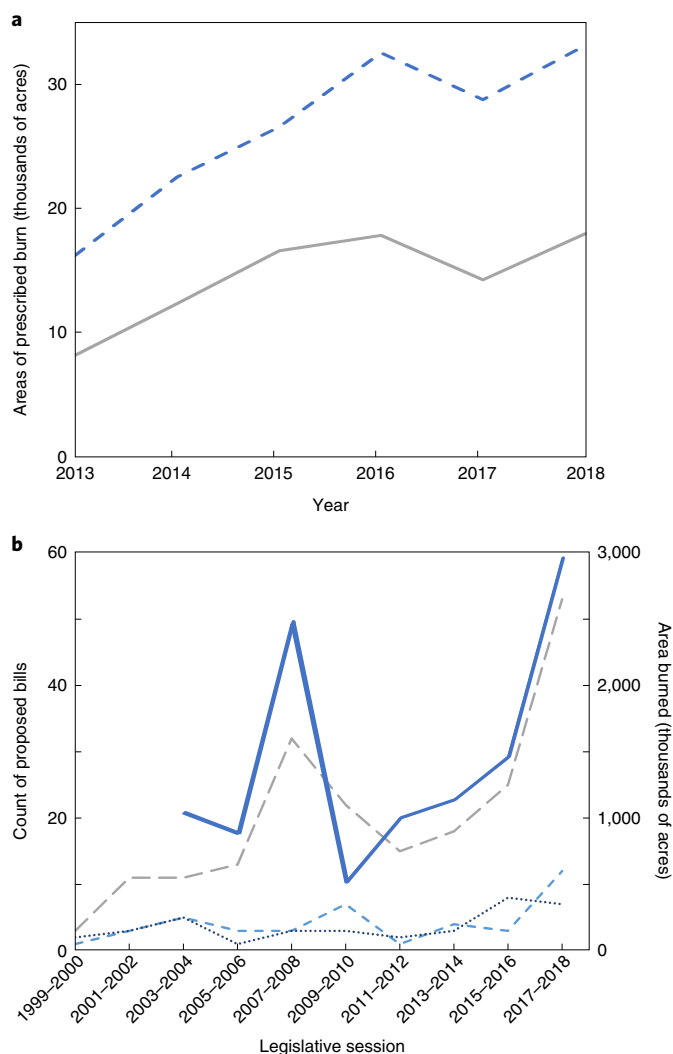
There is a notable gap between the acres planned for prescribed burning and the acres actually burned each year (Fig. 2a). The Prescribed Fire Information Reporting System (PFIRS) collects burn permit records from 22 of the 35 air districts in California<sup>17</sup>. To avoid reporting bias, we examined only the 16 local air districts that have consistently reported their burns to PFIRS since 2013. PFIRS records include planned and burned acres for individual burns registered within its system. Across consistently reporting local air districts, on average, 12,132 acres are planned but not burned each year (range across years: 8,070–15,201 acres), equivalent to between 38% and 51% of acres planned. This gap suggests that barriers prevent

thousands of acres from burning. Between 2013 and 2018, the acres planned rose by a factor of 2.04 (16,210 to 33,134 acres), and acres burned rose by a factor of 2.20 (8,140 to 17,933 acres). Of the 60,320 planned acres that were not burned (and with a known burner), a federal government agency planned 56,182 acres (93.1%) and, of these, the US Forest Service (USFS) planned 54,183 acres (96.4%). Escaped burns rarely occur, but those that do tend to remain small. Only 112 (1.76%) prescribed burns escaped, at an average of 13.61 acres.

Politicians propose more policies during years with worse wildfires (Fig. 2b). Analysis of wildfire-related bills reveals peaks during legislative sessions with more severe wildfires, as measured by acres burned per session. Wildfire bills spiked during the 2007–2008 and 2017–2018 sessions; 2008, 2017 and 2018 were record-setting years for wildfires (Fig. 2b)<sup>18</sup>. Fuel treatment bills also peaked during the 2017–2018 session, with 12 prescribed-burn and 7 thinning bills proposed.

**Perceptions of fuel treatments.** Policymakers and implementers view all treatments as valuable and recognized the need for dramatic increases in their deployment to mitigate wildfire risk (Table 1). Interview groups recognized the limitations associated with each type; prescribed burns are useful but underutilized, mechanical thinning serves as a default option and managed wildfire is possible only on federal property. Interviewees believed that prescribed burns support critical ecosystem functions. Federal employees recognized that the majority of land needing fuel treatments is federally owned. State government employees emphasized the public benefits associated with prescribed burns and the state's role in burning on state and private lands. Academics and non-profit representatives stressed choosing treatments based on fuel load and ecosystem type. The perspectives of non-profit representatives influenced those of state legislative staff and analysts, who viewed burns as ecologically beneficial but acknowledged their beliefs stemmed from prior conversations with constituents and non-profit representatives.

Interviewees believed they had a more favourable and nuanced view of prescribed burns than the general public, although many



**Fig. 2 | Trends in prescribed-burn implementation and wildfire-related proposed legislation. a**, Planned versus implemented prescribed-burn treatments. There is a gap between planned (dashed line) and burned (solid line) acres of prescribed burns. This gap reflects data reported by local air boards to PFIRS. Data taken from ref. <sup>17</sup>. **b**, Peaks in wildfire-related bills during legislative sessions with substantial wildfires. Count of wildfire (grey, wide-dashed line), prescribed burn (light blue, small dashed line) and thinning-related (dark blue, dotted line) bills by legislative session in California (left vertical axis) in the context of cumulative acres burned by wildfire (dark blue, solid line) per legislative session (right vertical axis). Wildfire-related bills experienced peaks during worse wildfire seasons. Prescribed burn- and thinning-related bills, which are subsets of the wildfire-related bills, experienced a peak in the 2017–2018 legislative session. Data taken from refs. <sup>18,48</sup>.

prior studies indicated public support for prescribed burns<sup>19,20</sup>. Interviewees believed (1) the public feared burns because of smoke and potential escapes, but education could change their minds, and (2) rural populations liked prescribed burns more than urban populations (Supplementary Table 3). First, interviewees offered anecdotes of public complaints that prevented burns and cases when sceptical local residents attended a burn, whereupon they became proponents. Second, interviewees recognized that rural populations had greater familiarity with, and appreciation of, burns than urban populations. These themes have been previously described and indicate familiarity with the public's concerns<sup>21–23</sup>. Interviewees viewed themselves as distinct from the general public regarding knowledge

of prescribed burns, given their roles as fuel management experts and policymakers, but they also understood the public's fears and the need to alleviate them.

Interviewees similarly believed mechanical thinning reduced fuel loads (particularly when combined with prescribed burns) and offered profit potential (unlike prescribed burns) (Table 1). Academics warned that the financial incentives offered by mechanical thinning may be elusive, given the high ratio of thinning to merchantable timber in many locations. Legislative staff and analysts criticized the traditional forestry model of removing large-diameter, valuable trees and leaving smaller, less valuable and more flammable biomass. However, they did not identify policy solutions that could incentivize more thinning of smaller biomass in conjunction with timber cutting. Other interview groups cautioned against viewing mechanical thinning as the default option unless used as a pretreatment in areas too dense for an initial prescribed burn. Non-profit representatives described their scepticism that companies harvesting timber would effectively reduce fuel loads and instead recommended using both thinning and burning. In contrast to the recent scientific literature, there is a strong sense among policymakers and implementers that dead or dying trees contribute to fire risk<sup>24,25</sup>.

Because managed wildfire is currently legal only on federal property, interviewees recognized that societal and political restrictions prohibit its wider use (Table 1). Managed wildfire involves more smoke and greater potential damage than prescribed burns. However, so long as these negative effects do not impact the public, interviewees believed managers should allow natural fires on remote federal land to burn and clear fuels. Interviewees from groups other than state government employees embraced it as natural, cost-effective and necessary to clear millions of acres needing fuel treatments. State legislative staff and analysts recognized that CAL FIRE is legally mandated to extinguish rather than enable wildfires, but some implied that this state-level restriction may change. Finally, and in contrast to other interview groups, state government employees expressed scepticism over managed wildfire's practicality. Although heralded as the future of fuel treatments by most interviewees, it remains unlikely that managed wildfire will be used on state and private land in the near future due to legal responsibilities and the need for cross-jurisdictional agreement. Interviewees therefore underscored the importance of expanding prescribed burns, particularly on non-federal lands, to achieve the ecological benefits of fire.

**Barriers to planning and implementing burns.** Prescribed burns do not occur due to three types of barriers: risks, limited resources and regulations. Risk-related barriers prevent landowners from beginning the process of planning to burn; limited resources and regulations prevent landowners from implementing steps to conduct a burn (Table 2). Interviewees indicated that specific barriers affect different types of landowners (Fig. 3).

Based on interviews, personal and public concerns regarding prescribed burns create risk-related barriers that prevent potential burners from beginning the burn planning process (Supplementary Table 3). First, all interview groups stated that liability laws place financial and legal responsibility for any escapes on the burners, resulting in a risk-averse culture that needs legal changes. Private landowners concerned about potential bankruptcy thus avoid burning on their property. Within the federal government, interviewees described an absence of praise or rewards for managers who used prescribed burns, but punishment for any escapes. Second, federal and state government employees claimed that negative public opinion remains a challenge, although opposition diminishes with education. Non-profit representatives believed that public tolerance for smoke or escapes is limited, and avoiding burns entirely can prevent any complaints (Table 2). Politicians have sought to address these challenges through new policies. Private landowners who

**Table 1 | Perspectives on fuel treatments by interview group**

Prescribed burns	Mechanical thinning	Managed wildfire
Federal government employees (n = 10)		
Necessary but underutilized (n = 10) “The prescribed fire programme is ineffective because we never burn at a scale temporally and spatially that is commensurate with the need ecologically or from a fuels management standpoint.”	Overemphasized, although necessary in dense areas (n = 10) “You couldn’t mechanically thin your way entirely toward restoration or forest resilience. You can get some of the way with thinning, and it’s a useful tool, but you need fire to really affect many of the processes.”	Necessary to address fire deficit (n = 10) “Managed wildfire lets us be successful on managing over long periods of time to achieve resource objectives that reduce the impact of unplanned fires... The future should be grounded in managed wildfire above all things.”
State government employees (n = 7)		
Recognized as providing public benefits (n = 5) “To reintroduce fire... is something that will provide a benefit to not only the natural resources of the state, the vegetation types of which that fire would be reintroduced, but also as a means of protecting communities and other assets at risk.”	Recognized as providing public benefits (n = 4) “To treat its vegetation types for purposes of restoration, purposes of fuel hazard reduction, purposes of a protection of assets, man-made and natural resources both.”	Not legally authorized for use on state or private property (n = 5) “Managed wildfire is very hard. I think the mechanism for managed wildfire has not been figured out yet, and the idea of what it looks like is a risky one.”
Legislative staff and analysts (n = 7)		
Viewed as a useful fuel treatment option (n = 4) “The best solution to dealing with dead and dying and diseased wood is increasing the role of fire in the forest.”	Underused, but not financially viable (n = 4) “The less valuable standing in the forest doesn’t pay its way out of the forest, so can we create a market for it?”	Currently limited at the state and private level (n = 3) “Probably a tool at the state level, but it’s more commonly thought of as a federal management tool on National Forest land.”
Non-profit representatives (n = 12)		
Recognized as useful to meet some ecological needs (n = 12) “We embrace all three [prescribed burns, mechanical thinning, and managed wildfire] at the right place and the right time.”	Overemphasized, but effective when combined with prescribed burns (n = 12) “I see thinning combined with prescribed burns as a tool for ecological restoration. It’s not comprehensive, but it can be a tool. I think it’s oversold and overused.”	Recognized as the likely future of fuel treatments (n = 12) “We need to get to a place where communities and stakeholders can be okay with managed wildfire. So that if it starts burning, we feel like we have the legal cover, social license, and planning capacity to go out and do it.”
Academics (n = 4)		
Useful for ecological and management objectives (n = 2) “Probably one of the most versatile and readily available tools available to managers... across the wider array of forest types, ecosystems, and both for more management-oriented objectives, but also for ecological objectives.”	Viewed as not financially viable (n = 2) “Mechanical treatments cost more [than burning] and don’t actually generate revenue from cutting trees. We need to balance the economics of it, the monetary input with the need to restore fire over a pretty large land area.”	Recognized as the likely future of fuel treatments (n = 3) “The only way we’re ever going to achieve an adequate amount of the right kind of fire back on these landscapes is if we manage natural ignitions to achieve that.”

Main themes and illustrative quotes are shown. Numbers in parentheses refer to counts of interviewees noting main theme.

enrol in a newly established certification and training programme or take appropriate precautions before burning are exempt from financial liability for any escapes (SB 1260)<sup>26</sup>. New public education programmes about prescribed burns were appropriated to improve public opinion (Executive Order B-52-18), although the programme’s details remain vague and may not expand beyond awareness campaigns<sup>27</sup>. These policies may result in more burns, particularly on private land.

Additionally, according to interviewees, resource- and regulations-related barriers create an implementation gap between acres planned and subsequently burned across landowner types (Fig. 3 and Table 2). First, the USFS, with its large, uninterrupted swathes of land, dedicated fire crew and agency approval of prescribed and managed burns, could burn hundreds of thousands of acres annually (Supplementary Table 4). However, wildfire suppression has historically diverted federal funding from wildfire prevention. Federal government employees and academics recommended strategic resource allocation between wildfire suppression and prevention. Non-profit representatives listed inconsistent funding for fuel treatments and an emphasis on private mechanical thinning as

limitations on prescribed burns in national forests. In many areas, overgrowth demands mechanical thinning pretreatments before prescribed burns, although financial constraints may limit follow-up burns. Second, interviewees across non-state government groups recognized a need for federal workforce rebuilding and training programmes. Active burn programmes have ended when experienced burn managers retired. An ageing federal workforce without newly trained burners has limited the use of prescribed burns. On the regulations side, the California Air Resources Board may establish narrow burn windows based on local weather conditions, restricting when or how many acres landowners can burn. Changing weather conditions may result in less burning than planned because burns cannot continue safely over consecutive days. Across interview groups, interviewees reported that land managers and air boards blamed each other: land managers claim that air boards do not offer enough burn days, but air boards claim that they offer more burn days than are used (Table 2). Similarly, federal government employees, legislative staff and non-profit representatives noted that local air boards may prohibit burning that would exceed air quality standards based on local weather conditions. These barriers remain.

**Table 2 | Barriers and proposed solutions to increasing deployment of prescribed burns**

Barrier	Count ( <i>n</i> = 40)	Sample quote	Potential solution
<b>Risk</b> (preventative)			
Liability laws	28 (70%)	"Avoidance of risk rather than taking risks. You continue to get your paycheck whether or not you get a burn off or not... [We need individuals] who are visionary, who are bold, and who get things done, and they're willing to take those risks."	Certified burners who undertake preventative efforts free from liability
Negative public opinion	35 (87.5%)	"I think the real issue around prescribed fire is an attitude issue and the culture."	Education programmes
<b>Resource and regulations</b> (limiting)			
<i>Federal</i>			
Limited funding	30 (75%)	"If we could have taken the amount of money that the recent Ferguson Fire cost and applied that to prescribed fires or managing wildfires, there would have been a cost saving."	Consistent funding for fire prevention
Limited training or certification programmes	14 (35%)	"I've seen really active, prescribed fire, managed wildfire programmes pretty much dry up overnight when someone retires."	Training or certification programme
Weather conditions	35 (87.5%)	"It is easy to scapegoat the air boards... We are given more burn days than we use."; "Wildfire smoke gets a pass, but we regulate prescribed burning because we light the match. That's silly. Smoke is smoke, and prescribed-burn smoke saves a ton of PM <sub>2.5</sub> emissions."	Standardization across air districts Reassessment of smoke from wildfires and prescribed burns in air quality standards Consistent adoption of PFIRS
<i>State and private</i>			
Inadequate firefighter availability	19 (47.5%)	"Are there ways to keep dedicated, prescribed fire crews when you've got this constant demand for wildland fires?"	Dedicated prescribed-burn crews Staggered seasonal prescribed-burn crews
Environmental regulations	12 (30%)	NEPA and CEQA "weren't meant to account for something like prescribed fire... You have to [do] CEQA for prescribed fire, which unfortunately means maybe you're burning every five to ten years, but that's about the time that your NEPA or CEQA document ends. And then you have to do it again."	No recommendation suggested

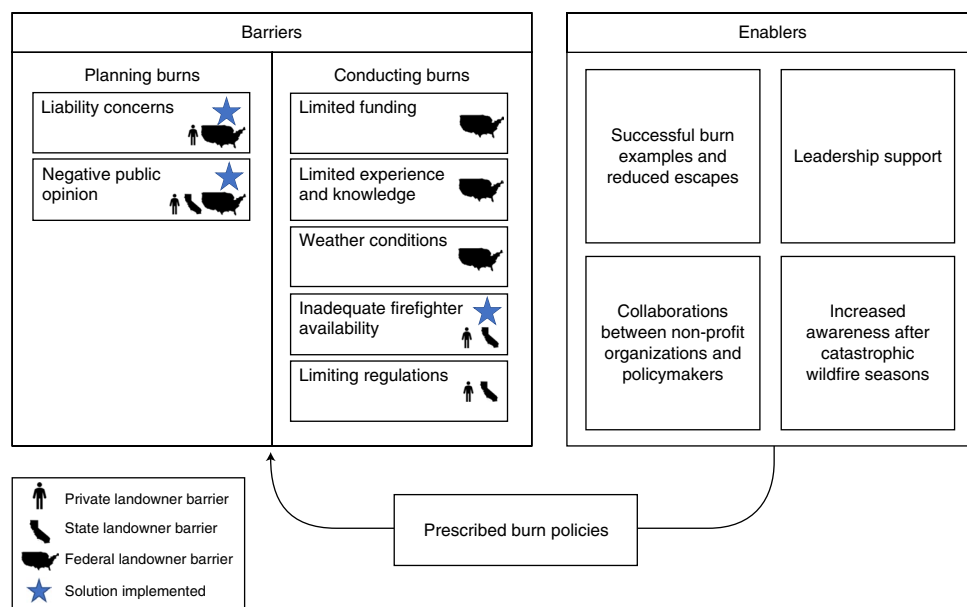
Identified barriers, illustrative quotes and interviewee-proposed solutions are shown. Numbers refer to counts of interviewees noting identified barriers.

State and private burners face two distinct resource- and regulations-related barriers identified by interviewees that contributed to a gap of 4,138 acres (6.86%) that were planned but not burned in PFIRS between 2013 and 2018 (Table 2 and Supplementary Table 4). First, all interview groups agreed that limited burn crew availability and prescribed-burn training or certification programmes restrict when and where burns can occur. Before 2018, California had no official prescribed-burn training or certification programme. Private landowners therefore had few opportunities to practice burning safely, exacerbating liability apprehensions. Many CAL FIRE crews are seasonal rather than full-time employees hired during the worst wildfire months rather than the best prescribed-burn months. CAL FIRE can divert crews from conducting planned burns to extinguishing wildfires in other regions of the state, limiting the use of VMP contracts. Second, interviewees from all groups except academics identified state and cross-jurisdictional regulations as slowing or preventing fuel treatments. Burners receiving federal or state funds must undergo environmental reviews mandated by the National Environmental Protection Act or the California Environmental Quality Act. Burn managers who miss the window of approval by these potentially expensive and time-consuming reviews must redo the process, preventing an otherwise planned burn from occurring. For example, VMP contracts may

expire before plans receive CEQA approval. Interviewees complained that these laws, intended for determining environmental impacts of major projects or actions, are not applicable for prescribed burns, which should occur regularly. These barriers broadly remain, although a new state-level training and certification programme may increase private burning.

**Enablers to deploy prescribed burns.** Interviewees identified three factors that contributed to a recent rise in prescribed burn use, primarily on non-federal land: infrequent escapes, strong leadership and political collaborations (Fig. 3 and Table 2). First, small and infrequent escapes demonstrated the safety of using burns to create fuel breaks that aided firefighting efforts (Supplementary Table 5). According to federal government employees, escapes occurred infrequently because of caution and preparation during deployment, although risk-related barriers may also contribute. Second, all interview groups claimed that successful burns generated political support from powerful state government officials (for example, former Governor Jerry Brown and former CAL FIRE director Ken Pimlott), which enabled policy and culture shifts in their favour. Interviewees, particularly among non-profit representatives, recognized that high-level policy directives require time for implementation and hoped future administrations could maintain political enthusiasm





**Fig. 3 | Barriers and enablers to deploying prescribed burns.** Two barriers prevent burns from being planned, and five barriers prevent burns from being conducted across federal (F), state (S) and private (P) land. Barriers preventing burns from being planned include liability concerns (F, P) and negative public opinion (F, S, P). Barriers preventing burns from being conducted include limited funding (F), limited experience and knowledge (F), weather conditions (F), inadequate firefighter availability (S, P) and environmental regulations (S, P). New prescribed-burn policies stem from a combination of successful burns, leadership support, collaborations and political willpower generated by catastrophic wildfire seasons. New policies have included solutions that may address barriers to liability concerns, negative public opinion and inadequate firefighter availability.

for prescribed burns. Finally, interviewees believed that collaborations and conversations across non-profit organizations and state legislators improved legislators' perception of burns, resulting in new bills. Furthermore, non-profit organizations, CAL FIRE and several federal agencies signed a Memorandum of Understanding for the Purpose of Increasing the Use of Fire to Meet Ecological and Other Management Objectives<sup>28</sup> in 2015. When asked, interviewees said the Memorandum reminded signatories of their commitment to return fire, prescribed or managed, to California's landscape.

Recent wildfires created political opportunities within the state government that enabled the implementation of new policies. All interview groups, and with unanimous agreement among legislative staff interviewed, emphasized the critical role of the 2017 wildfires for executive and legislative action, particularly for prescribed burns (Fig. 3). The severity of these fires established political space for state legislators to introduce wildfire- and fuel treatment-related bills in the 2017–2018 legislative session. Many of these bills emerged from prior discussions with legislators on fuel treatments to promote forest health following the drought and tree mortality crisis from the early 2010s. Interviewees expressed concern that a light wildfire season following 2017 could give legislators license to focus on non-wildfire priorities. Interviewees stressed the importance of maintaining that pressure, since one legislative session could not resolve all wildfire issues. Interviews occurred between June and October 2018, so interviewees did not yet know that the most destructive wildfire in California's history would occur later that year (Camp Fire).

Interviewees praised the new policy changes intended to address risk-related barriers and identified potential solutions to the resource- and regulations-related barriers (Table 2). For example, dedicated fuel treatment funding could prevent funding fluctuations. Prescribed-burn smoke contributes to anthropogenic emissions, whereas wildfires count as natural emissions<sup>29</sup>. Changes to emissions calculations may incentivize treatments. According to interviewees, standardization across air boards may establish greater consistency in burn occurrence, particularly in areas crossing multiple jurisdictions. Air boards keep inconsistent reports; state-wide

adoption of PFIRS could improve burn records. Interviewees also suggested that dedicated prescribed burn or staggered seasonal fire crews and more training for federal employees could address limited firefighter availability. Interviewees proposed no recommendations for environmental regulations because they did not want to lessen overall environmental protections.

## Discussion

Perspectives offered by policymakers and implementers may offer important insights about what could, should or would be done. For example, academics and government employees probably have the best understanding of the limitations and opportunities for prescribed burns, whereas non-profit representatives and legislative staff probably have the greatest means to design or influence new policies. The former groups emphasize specific challenges facing greater deployment (for example, limited trained burners), while non-profit representatives and legislative staff tend to focus on the practical means to address these challenges (for example, establish training programmes), indicating that practitioners are communicating their needs to policymakers.

The severity of the 2017 and 2018 wildfires, combined with infrequent escapes, political support and collaborations between legislators and experts, enabled the development and implementation of new prescribed-burn policies. Policymakers often respond to catastrophes with new proposals<sup>30,31</sup>, consistent with our review of wildfire-related bills. Based on interviews and aligned with the prior literature, it is found that inconsistent funding<sup>32,33</sup>, narrow burn windows, inadequate firefighter availability<sup>8,33,34</sup>, limited prior experience<sup>22,34</sup> and environmental regulations<sup>8,35</sup> generate the gap between planned and implemented burns illustrated by PFIRS data. In addition, and similar to prior literature, interviewees identified negative public opinion<sup>8</sup> and liability concerns<sup>22,36</sup> as barriers preventing burners from beginning the burning process.

Similar policy-related impediments exist in South Africa<sup>37,38</sup>, the Mediterranean<sup>39,40</sup> and Australia<sup>41,42</sup>. By contrast, many such policy-related impediments are not applicable in the southeastern United

States, where weather and climatic conditions, liability laws and public acceptance and tolerance are more favourable to prescribed burns<sup>3</sup>. Climatic differences aside, new liability laws and growing public support for prescribed burns could indicate movement toward the prescribed-burn model of states such as Florida.

Addressing the 20 million acres in California in need of fuel treatments will require more treatment options than only prescribed burns. Through interviews, practitioners demonstrated an intention to increase fuel treatments and mitigate the wildfire threat. However, current policies, practices and recommendations appear too conservative to meet recommended fuel treatment goals, particularly on state and private land. Recent proposals focus on reducing disincentives (for example, addressing liability concerns) on state and private lands rather than incentivizing or enforcing fuel treatments across federal and non-federal lands.

Future catastrophic wildfires may motivate legislators to propose additional preventative policies in California. However, interviewee-identified solutions, such as dedicated prescribed-burn crews or consistent adoption of PFIRS, would probably enable incremental changes rather than a radical reshaping and expansion of priorities, investments and planning. Treating the recommended 1.01 million acres per year<sup>6</sup> will require matching treatment type to local conditions<sup>43</sup> and implementing creative solutions that employ all possible fuel treatments across federal and, particularly, non-federal land. Augmenting firefighting and prescribed-burn crews could facilitate more burns. CAL FIRE currently offers minimal financial support for projects to reduce fire severity on private lands, and the limited profitability of small biomass results in inadequate mechanical treatments<sup>44</sup>. Incentives for fuel reduction on private land or biomass sales could engender more fuel treatments. Managed wildfire could become possible on remote state or private properties with landowner permission if the legal restriction on CAL FIRE is lifted. Regardless of other policy changes, robust enforcement of federal and non-federal fuel treatment goals is critical to ensure adequate reduction in wildfire risk. Generating the political willpower to make these important policy changes will probably require a combination of administration support, successful burns, collaboration among multiple stakeholders and, unfortunately, more deadly and destructive wildfires.

## Methods

**Summary.** This is an empirical study of trends, challenges and opportunities for the deployment of prescribed burns in California. The empirical results draw on prescribed-burn records from PFIRS, proposed legislation from the California State Legislature and 40 interviews with 45 key stakeholders, conducted between June and October 2018 by the authors. The study compares prescribed-burn records submitted by landowners with counts of proposed policies by the state legislature to generate new hypotheses related to different types of barriers preventing prescribed burns and the role of recent wildfires in fuel treatment policies. These hypotheses have been further explored and tested with primary interview data. Because of the heavy reliance on interview data, these results cannot be completely replicable.

**Prescribed-burn permits.** To examine state-wide trends in prescribed-burn permits and use throughout California, we reviewed records from PFIRS between 2012 and 2018. The California Air Resources Board collects data on planned and conducted prescribed burns for 22 of California's 35 local air pollution control districts (APCDs) or air quality control districts (AQCDs) through PFIRS. Records from 2012 were incomplete, limiting us to the use of data between 2013 and 2018 from the 16 local air boards that had consistently used PFIRS during this period, regardless of frequency of prescribed burns. PFIRS includes data from Butte County (\*), Calaveras County (\*), Colusa County (\*), Eastern Kern (\*), El Dorado County (\*), Feather River (\*), Glenn County (\*), Great Basin Unified (\*), Lake County, Mariposa County, Monterey Bay Unified (\*), Northern Sierra (\*), Northern Sonoma County, Placer (\*), Sacramento Metro (\*), San Joaquin Valley (\*), Santa Barbara County, Shasta County (\*), Siskiyou County, Tehama County (\*), Tuolumne County (\*) and Yolo-Solano; asterisks indicate the counties that used PFIRS consistently between 2013 and 2018. Data were not available from the remaining 13 APCDs and AQCDs in a comparable format to PFIRS.

PFIRS records included information on burn dates, acres planned and actually burned, managing agency, county, air district and air basin. Managing

agency referred to type of burner or landowner (for example, USFS or CAL FIRE). After deduplication and removal of 'unknown' and 'test APCD' burns, the PFIRS database listed 6,663 individual burns between 2013 and 2018, although not all burns in the database included all types of information. Researchers have previously defined escaped burns as prescribed burns that subsequently became wildfires or entered property not owned by the burner<sup>45,46</sup>, but PFIRS records do not include indications of whether the prescribed burns became wildfires. Therefore, and to account for small variations during a burn, we defined escaped burns as those in which the acres burned exceeded the acres planned by more than 5% and the escaped burn size was greater than or equal to 0.5 acres. Of the 6,663 individual burns in PFIRS, 6,373 (95.65%) of the prescribed burns included data on acres planned and burned; as described in the text, escapes occurred in 112 of these 6,373 cases (1.76%). On average, escaped burns covered 13.61 additional acres beyond those planned<sup>47</sup>.

The National Interagency Fire Center (NIFC) in Boise, Idaho, also collects information on prescribed burns in each state. NIFC presents data on prescribed burns based on the location in which they start. According to the NIFC, prescribed burns occurred on 205 acres of state, county or private land between 2013 and 2017, compared to 228,639 acres on federal land<sup>48</sup>. These values contradict those in PFIRS and include less detail than the PFIRS records. These two datasets are different and each has limitations. PFIRS provides yearly data on proposed and actual acres burned by landowner, but only from air boards that volunteer the information. NIFC provides yearly data on total acres burned as reported to NIFC rather than from individual air districts or boards. We therefore did not include NIFC data in this portion of the analysis.

**Wildfire-related legislation.** To determine changes in wildfire-related legislation over time, we examined proposed legislation from the California State Legislature between the 1999–2000 and 2017–2018 legislative sessions. The 'Bill Search' function returned bills dating back to the 1999–2000 legislative session with the keywords 'wildfire', 'prescribed/controlled burn/fire' and 'thinning'. A review of all bills ensured relevance. For example, bills dedicating portions of the highway to a firefighter were excluded as irrelevant to fuel treatments. Annual budgetary bills pertaining to wildfires were also excluded from counts. For the purposes of this study, relevant legislation included bills proposing new programmes, the establishment of new funding mechanisms or oversight bodies for land or wildfire management, alterations to existing government code, disaster relief and public safety or information improvements.

We also recognize the difference between proposed, chaptered and appropriated bills. Proposed bills are described in 'Current state of prescribed burns'. Chaptered bills represent proposed bills that have been approved by both the State Senate and State Assembly, and have received approval from the governor. Chaptered bills have therefore become law. Appropriated bills have moved through the Appropriations Committees in the Senate or Assembly and typically indicate that funding is needed to implement the bill effectively. Chaptered and appropriated bills may be used as a proxy for legislation with the capacity to enact change because the annual budget should include funding for such bills.

Before the 2017–2018 legislative session, 28 wildfire bills had been chaptered and appropriated out of 150 (18.7%) proposed bills. Of these, 10 wildfire bills were chaptered and appropriated during the 2007–2008 wildfire season, which was also during the legislative session with the second most severe wildfires, after 2017–2018. During the 2017–2018 legislative session, 16 out of the 53 (30.2%) proposed wildfire bills were chaptered and appropriated. Before the 2017–2018 legislative session, only 3 prescribed-burn bills had been chaptered and appropriated out of 30 (10%) proposed bills. During the 2017–2018 legislative session, 6 out of the 12 (50%) prescribed-burn bills were chaptered and appropriated. Similarly, before the 2017–2018 legislative session, only 1 thinning bill had been chaptered and appropriated out of 30 (3.3%) proposed bills. During the 2017–2018 legislative session, 3 of the 7 (42.9%) thinning bills were chaptered and appropriated. These trends suggest that legislators enacted more legislation with the capacity to enact change related to wildfires, prescribed burns and thinning during the 2017–2018 legislative session than in preceding legislative sessions<sup>44</sup>.

Information on acres burned from wildfire seasons came from total acres burned in California according to the NIFC during each of the two-year legislative sessions. NIFC data from California became available in 2002 (ref. <sup>48</sup>).

**Interview sampling strategy.** Potential interviewees were identified through association with California's current or proposed prescribed-burn policies. We constructed a list of policymakers, practitioners and researchers involved in investigating questions surrounding prescribed burns, designing or implementing policies related to prescribed burns, or conducting prescribed burns. Interviewees came from a range of institutions and agencies (federal government, state executive branch, state legislative branch, non-profit organizations and academics). Because private landowners have limited direct impact on designing new policies beyond individual lobbying or donations, their perspectives were not captured beyond the constituent views described by legislative staff. Lobbying and donations represent means by which private citizens can influence the policy process, but private citizens remain outside the direct policymaking process. Instead, interviews with policymakers and implementers revealed what they perceived to be the

barriers and enablers for increasing the deployment of prescribed burns based on constituent communications and experiences, including those from private landowners. Snowball sampling was used to identify additional participants, as interviewees recommended a diverse array of participants with a range of views. This resulted in a list of 58 potential interviewees. We contacted all interviewees with available contact information, with the final sample of interviewees determined by availability and interest in participation. Of the 18 interviews that did not occur, 12 interviewees did not respond and 6 did not wish to participate. This resulted in interviews with over half of the total interviewee pool (69%).

The 45 interviewees included 37 men (82%) and 8 women (18%). Three interviewees brought one or two colleagues to the interview (resulting in a total of 45 interviewees and 40 interviews). The study included 10 interviews with federal government employees (25%), 7 with state government employees (17.5%), 7 with legislative staff or analysts (17.5%), 12 with non-profit representatives (30%) and 4 with academic researchers or affiliates (10%). Supplementary Table 2 lists interviewee affiliations in greater detail.

**Interview procedure.** The interviews were semistructured, using a protocol interview guide. All interviews included an opportunity for the interviewee to ask questions and provide informed consent. All interviewees received assurances of confidentiality and a guarantee of anonymity beyond affiliation with their organization, following the ethical guidelines and approval from the Stanford University Institutional Review Board. Interviewees answered questions on their opinions of different fuel treatment techniques, proposed prescribed-burn policies, the influence of the 2017 and 2018 wildfire seasons on the policies, the challenges in implementing prescribed burns in California and opportunities to increase their deployment. Interviews were conducted either in person or by telephone. Interviews lasted between 45 and 60 minutes. All interviews were recorded and transcribed, with interviewee consent.

**Interview data analysis.** The interview transcripts were coded in NVivo and Excel to identify quotes under ten key themes: opinions of fuel treatments, challenges, public opinion, collaboration, successes, the role of individuals, climate change, the 2017 wildfire season, the 2018 wildfire season and policy changes. These themes stemmed from the literature and from grounded theory analysis of the interviews. Some themes linked explicitly to questions posed to the interviewees (for example, what their opinions were of prescribed burns, mechanical thinning and managed wildfires), while others were not mentioned in interview questions and emerged naturally during the discussions. For example, no questions were asked about the role of individuals or climate change. The coding occurred through thematic association by question, using grounded theory to identify themes and recode interviews in an iterative process. Interview results were reviewed thematically, individually and by group affiliation (for example, non-profit organization or academia). Strong similarities across individuals with the same group affiliation enabled us to cluster results by the five group affiliations, as presented in the main text and Supplementary Tables 1–5. Interview results may not indicate broader trends, as they occurred during major wildfire seasons.

**Ethics statement.** This work has been approved by the Stanford University Institutional Review Board. All interviewees provided informed consent. The informed consent for this work involves anonymized interview data and confidential storage of the complete data set.

## Data availability

For the interviews, the data that support the findings of this study are available from the corresponding author on request and under limits permissible by the Institutional Review Board. The data are not publicly available due to them containing information that could compromise research participant privacy/consent.

For PFIRS, the data that support the findings of this study are available on request from the California Air Resources Board's Prescribed Fire Information Reporting System (<https://ssl.arb.ca.gov/pfirs/>).

Source data on bills are available from the California State Legislature (<http://leginfo.ca.gov/faces/billSearchClient.xhtml>) and are provided within the paper. Source data on acres burned are available from the National Interagency Fire Center's Historical year-end fire statistics by state (source NICC) ([https://www.nifc.gov/fireInfo/fireInfo\\_statistics.html](https://www.nifc.gov/fireInfo/fireInfo_statistics.html)) and are provided within the paper.

Received: 17 June 2019; Accepted: 12 November 2019;  
Published online: 20 January 2020

## References

- Dennison, P. E., Brewer, S. C., Arnold, J. D. & Moritz, M. A. Large wildfire trends in the western United States, 1984–2011. *Geophys. Res. Lett.* **41**, 2928–2933 (2014).
- Abatzoglou, J. T. & Williams, A. P. Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl Acad. Sci. USA* **113**, 11770–11775 (2016).
- Ryan, K. C., Knapp, E. E. & Varner, J. M. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Front. Ecol. Environ.* **11**, e15–e24 (2013).
- Steel, Z. L., Safford, H. D. & Viers, J. H. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**, 1–23 (2015).
- North, M., Collins, B. M. & Stephens, S. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *J. For.* **110**, 392–401 (2012).
- California Forest Carbon Plan: Managing our Forest Landscapes in a Changing Climate (Forest Climate Action Team, 2018).
- Boisramé, G., Thompson, S., Collins, B. & Stephens, S. Managed wildfire effects on forest resilience and water in the Sierra Nevada. *Ecosystems* **20**, 717–732 (2017).
- Quinn-Davidson, L. N. & Varner, J. M. Impediments to prescribed fire across agency, landscape and manager: an example from northern California. *Int. J. Wildland Fire* **21**, 210–218 (2011).
- Syphard, A. D., Scheller, R. M., Ward, B. C., Spencer, W. D. & Strittholt, J. R. Simulating landscape-scale effects of fuels treatments in the Sierra Nevada, California, USA. *Int. J. Wildland Fire* **20**, 364–383 (2011).
- Prichard, S. J., Peterson, D. L. & Jacobson, K. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. *Can. J. Res.* **40**, 1615–1626 (2010).
- Kobziar, L. N., McBride, J. R. & Stephens, S. L. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. *Int. J. Wildland Fire* **18**, 791–801 (2009).
- North, M. et al. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. *J. For.* **113**, 40–48 (2014).
- Stephens, S. L. et al. The effects of forest fuel-reduction treatments in the United States. *BioScience* **62**, 549–560 (2012).
- Cochrane, M. A. et al. Estimation of wildfire size and risk changes due to fuels treatments. *Int. J. Wildland Fire* **21**, 357–367 (2012).
- Safford, H. D., Stevens, J. T., Merriam, K., Meyer, M. D. & Latimer, A. M. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *For. Ecol. Manag.* **274**, 17–28 (2012).
- Fernandes, P. M. & Botelho, H. S. A review of prescribed burning effectiveness in fire hazard reduction. *Int. J. Wildland Fire* **12**, 117–128 (2003).
- Prescribed Fire Information Reporting System Data Set (California Air Resources Board, 2019); <https://ssl.arb.ca.gov/pfirs/index.php>
- Bill Information Data Set (California Legislative Information, 2019); <http://leginfo.ca.gov/faces/billSearchClient.xhtml>
- Toman, E., Shindler, B., McCaffrey, S. & Bennett, J. Public acceptance of wildland fire and fuel management: panel responses in seven locations. *Environ. Manag.* **54**, 557–570 (2014).
- McCaffrey, S. M. & Olsen, C. S. *Research Perspectives on the Public and Fire Management: A Synthesis of Current Social Science on Eight Essential Questions* JFSP Synthesis Reports 17 (Univ. Nebraska-Lincoln, 2012); <http://digitalcommons.unl.edu/jfspsynthesis/17>
- Weissaupt, B. R., Carroll, M. S., Blatner, K. A., Robinson, W. D. & Jakes, P. J. Acceptability of smoke from prescribed forest burning in the northern inland west: A focus group approach. *J. For.* **103**, 189–193 (2005).
- Morton, L. W., Regen, E., Engle, D. M., Miller, J. R. & Harr, R. N. Perceptions of landowners concerning conservation, grazing, fire, and eastern red cedar management in tallgrass prairie. *Rangel. Ecol. Manag.* **63**, 645–654 (2010).
- Toman, E., Stidham, M., Shindler, B. & McCaffrey, S. Reducing fuels in the wildland-urban interface: community perceptions of agency fuels treatments. *Int. J. Wildland Fire* **20**, 340–349 (2011).
- Stephens, S. L. et al. Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* **68**, 77–88 (2018).
- Lalonde, S. J. et al. Forest management in the Sierra Nevada provides limited carbon storage potential: an expert elicitation. *Ecosphere* **9**, e02321 (2018).
- Jackson, H. B. SB-1260 Fire Prevention and Protection: Prescribed Burns [http://leginfo.ca.gov/faces/billNavClient.xhtml?bill\\_id=20170180SB1260](http://leginfo.ca.gov/faces/billNavClient.xhtml?bill_id=20170180SB1260) (2018).
- Executive Department, State of California. Executive Order B-52-18 <https://www.gov.ca.gov/wp-content/uploads/2018/05/5.10.18-Forest-EO.pdf> (2018).
- US Forest Service. Memorandum of Understanding for the Purpose of Increasing the Use of Fire to Meet Ecological and Other Management Objectives <https://www.sierraforestlegacy.org/Resources/Community/PrescribedFire/FireMOUSigned.pdf> (2015).
- Engel, K. H. Perverse incentives: the case of wildfire smoke regulation. *Ecol. Law Q.* **40**, 623–672 (2013).
- Pralle, S. B. Agenda-setting and climate change. *Env. Polit.* **8**, 781–799 (2009).
- Birkland, T. A. & Warnement, M. K. in *Decision-Making under Ambiguity and Time Constraints: Assessing the Multiple-Streams Framework* (eds Zohlnhöfer, R. & Rüb, F. W.) Ch. 6 (ECPR Press, 2016).
- Stephens, S. L., Collins, B. M., Biber, E. & Fulé, P. Z. U.S. federal fire and forest policy: emphasizing resilience in dry forests. *Ecosphere* **7**, 1–19 (2016).



33. North, M. P. et al. Reform forest fire management. *Science* **349**, 1280–1281 (2015).
34. Schultz, C. et al. *Prescribed Fire Policy Barriers and Opportunities: A Diversity of Challenges and Strategies Across the West Ecosystem Workforce Program Working Paper No. 86* (Univ. Oregon, 2018).
35. Everett, Y. & Fullet, M. Fire safe councils in the interface. *Soc. Nat. Resour.* **24**, 319–333 (2011).
36. Toledo, D., Kreuter, U. P., Sorice, M. G. & Taylor, C. A. Jr. To burn or not to burn: ecological restoration, liability concerns, and the role of prescribed burning associations. *Rangelands* **34**, 18–23 (2012).
37. van Wilgen, B. W., Forsyth, G. G. & Prins, P. The management of fire-adapted ecosystems in an urban setting: the case of Table Mountain National Park, South Africa. *Ecol. Soc.* **17**, 8 (2012).
38. van Wilgen, B. W., Forsyth, G. G., de Klerk, H., Das, S. & Khuluse, S. Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *J. Appl. Ecol.* **47**, 631–638 (2010).
39. Fernandes, P. M. et al. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. *Front. Ecol. Environ.* **11**, e4–e14 (2013).
40. Ascoli, D. & Bovio, G. Prescribed burning in Italy: issues, advances and challenges. *IFOREST* **6**, 79–89 (2013).
41. Burrows, N. & McCaw, L. Prescribed burning in southwestern Australian forests. *Front. Ecol. Environ.* **11**, e25–e34 (2013).
42. McCaw, W. L. Managing forest fuels using prescribed fire—a perspective from southern Australia. *For. Ecol. Manag.* **294**, 217–224 (2013).
43. Calkin, D. E., Cohen, J. D., Finney, M. A. & Thompson, M. P. How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proc. Natl Acad. Sci. USA* **111**, 746–751 (2014).
44. Little Hoover Commission. *Fire on the Mountain: Rethinking Forest Management in the Sierra Nevada* <https://lhc.ca.gov/sites/lhc.ca.gov/files/Reports/242/Report242.pdf> (2018).
45. Kolden, C. A. & Brown, T. J. Beyond wildfire: perspectives of climate, managed fire and policy in the USA. *Int. J. Wildland Fire* **19**, 364–373 (2010).
46. State of California. *Public Resources Code Section 4422* [https://leginfo.ca.gov/faces/codes\\_displaySection.xhtml?lawCode=PRC&sectionNum=4422.&article=2.&highlight=true&keyword=burn+escape](https://leginfo.ca.gov/faces/codes_displaySection.xhtml?lawCode=PRC&sectionNum=4422.&article=2.&highlight=true&keyword=burn+escape) (2019).
47. Finney, M. A. et al. Simulation of long-term landscape-level fuel treatment effects on large wildfires. *Int. J. Wildland Fire* **16**, 712–727 (2007).
48. National Interagency Fire Center. *Statistics* [https://www.nifc.gov/fireInfo/fireInfo\\_statistics.html](https://www.nifc.gov/fireInfo/fireInfo_statistics.html) (2018).

## Acknowledgements

B. Cain and L. Ortolano provided feedback on a draft version of the manuscript. This work has been funded by an E-IPER Summer Research Grant and a McGee Research Grant.

## Author contributions

R.K.M., C.B.F. and K.J.M. conceived and designed the research. R.K.M. conducted interviews and analysed the data. R.K.M., C.B.F. and K.J.M. contributed to results and discussion. R.K.M. wrote the paper. C.B.F. and K.J.M. provided comments.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** is available for this paper at <https://doi.org/10.1038/s41893-019-0451-7>.

**Correspondence and requests for materials** should be addressed to R.K.M.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2020